

$\Psi(2S)$, $\Upsilon(3S)$ Suppression in p-Pb, Pb-Pb Collisions and Mixed Hybrid Theory

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Abstract

We use our mixed hybrid model for the $\Psi(2S)$ state to estimate $\Psi(2S)$ to $J/\Psi(1S)$ suppression in p-Pb collisions, and the $\Upsilon(3S)$ state to estimate $\Upsilon(3S)$ to $\Upsilon(1S)$ suppression in Pb-Pb collisions, and compare to recent experimental measurements.

1 Introduction

The production of Ψ and Υ mesons via $p - p$ collisions has been of interest for many years as a test of QCD (Quantum Chromodynamics). More than a decade ago it was shown that the relative production of $\Psi(2S)$ to $J/\Psi(1S)$ in $p - \bar{p}$ collisions was not consistent with standard QCD models[1]. Similarly, in experiments on $\Upsilon(nS)$ production via $p - p$ collisions it was found[2, 3] that $\Upsilon(3S)$ to $\Upsilon(1S)$ production is also not consistent with standard QCD models. In a theoretical study of Ψ and Υ production via $p - p$ or $p - \bar{p}$ collisions[4] it was shown that the relative probabilities of $\Psi(2S)$ to $J/\Psi(1S)$ and $\Upsilon(3S)$ to $\Upsilon(1S)$ are consistent with experiment if the $\Psi(2S)$ and $\Upsilon(3S)$ are mixed heavy hybrids, discussed below. The fact that $\Psi(2S)$ is a mixed charmonium hybrid meson and $\Upsilon(3S)$ is a mixed bottomonium hybrid meson, while $J/\Psi(1S)$ and $\Upsilon(1S)$ are standard charmonium and bottomonium mesons is the basis for the present work.

Recent experiments using $d - Au$ collisions[5, 6] and $p - Pb$ collisions[7, 8] have shown a strong suppression, S_A , of $\Psi(2S)$ relative to $J/\Psi(1S)$. As stated in these articles, this suppression cannot be explained by current theoretical models[9, 10, 11, 12, 13]. In an earlier study of J/Ψ production and absorption[14] two scenarios were used for charmonium production: 1. charmonium states are produced with the $c\bar{c}$ a color octet ($|c\bar{c}(8)g\rangle$); and 2. charmonium states are produced as a color singlet $|c\bar{c}\rangle$, which is the standard model.

In the present work on $\Psi(2S)$ suppression scenario 1. of Ref[14] is used, as is discussed in Ref[4]. We estimate S_A for both $J/\Psi(1S)$ and $\Psi(2S)$ for $p - Pb$ collisions using the mixed heavy hybrid theory, and show that the ratio of S_A for $\Psi(2S)$ to $J/\Psi(1S)$ is consistent with experiments. CMS experiments have measured Υ states suppression in Pb-Pb collisions[15, 16], and estimated the yields of $\Upsilon(3S)/\Upsilon(1S)$ relative to those in p-p collisions[16]. We estimate this ratio using our mixed hybrid theory.

Next we briefly discuss the method of QCD Sum Rules, and how this was used to show that the $\Psi(2S)$ and $\Upsilon(3S)$ are mixed heavy hybrids, defined in the next section.

2 Mixed Heavy Hybrid States via QCD Sum Rules

The starting point of the method of QCD sum rules[17] for finding the mass of the state referred to as A is the correlator,

$$\Pi^A(x) = \langle |T[J_A(x)J_A(0)]| \rangle, \quad (1)$$

with $| \rangle$ the vacuum state and the current $J_A(x)$ creating the states with quantum numbers A . The QCD sum rule is obtained by equating a dispersion relation of Π^A in momentum space to an operator product expansion of Π^A using QCD diagrams with quarks and gluons. After taking a Borel transform[17], \mathcal{B} , in which the momentum variable is replaced by the Borel mass, M_B , the QCD sum rule has the form

$$\frac{1}{\pi}e^{-M_A^2/M_B^2} + \mathcal{B} \int_{s_0}^{\infty} \frac{Im[\Pi_A(s)]}{\pi(s - q^2)} ds = \mathcal{B} \sum_k c_k^A(q) \langle 0 | \mathcal{O}_k | 0 \rangle, \quad (2)$$

where M_A is the lowest mass of a state with the properties of A and the right-hand side is the Borel transform of the operator product expansion of Π^A . The operator that produces the mixed charmonium and hybrid charmonium states, with b determined from the Sum Rule, is

$$J_{C-HC} = bJ_H + \sqrt{1 - b^2}J_{HH}, \quad (3)$$

with $J_H|0\rangle = |c\bar{c}(0)\rangle$, $J_{HH}|0\rangle = |[c\bar{c}(8)g](0)\rangle$, where $|c\bar{c}(0)\rangle$ is a standard Charmonium state, while a hybrid Charmonium state $|[c\bar{c}(8)g](0)\rangle$ has $c\bar{c}(8)$ with color=8 and a gluon with color=8. For the mixed hybrid Charmonium state produced by J_{C-HC} mass M_A of Eq(2) is called M_{C-HC} . To find the mass M_{C-HC} one plots the value of M_{C-HC}^2 vs M_B^2 using Eq(2) with the quantities derived in Ref.[18]. The solution for M_{C-HC} is given by the minimum in the plot. Note that $M_{C-HC} \simeq M_B^2$ for a solution satisfying the method of QCD Sum Rules. This plot is shown in the figure below for (Eq(3)) $b^2 = 0.5$.

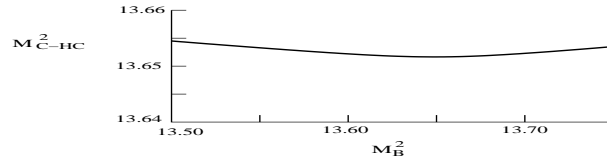


Figure 1: Mixed Charmonium-hybrid charmonium mass $\simeq 3.65$ GeV

From this figure one sees that the minimum in $M_{C-HC}^2(M_B^2)$ corresponds to the $\Psi'(2S)$ state, with a mass[19] of 3.686 GeV. Therefore the $\Psi'(2S)$ meson is 50% normal Charmonium and 50% hybrid Charmonium, while the $J/\Psi(1S)$ is a normal Charmonium meson. The analysis for Upsilon states was similar, with the $\Upsilon(3S)$ being 50% normal Bottomonium and 50% hybrid Bottomonium, while the $\Upsilon(1S)$ and $\Upsilon(2S)$ states are standard Bottomonium mesons. We shall use this to estimate the ratio of suppression of $\Psi(2S)$ to $J/\Psi(1S)$ in p-Pb collisions and $\Upsilon(3S)$ to $\Upsilon(3S)$ in Pb-Pb collisions.

3 Nuclear Modification and Suppression of $\Psi(2S)/J/\Psi(1S)$ in p-Pb Cossisions

In this section we derive the relative suppression of $\Psi(2S)$ to $J/\Psi(1S)$ and compare this result to experiment. First the definition of nuclear suppression and experimental data for the relative $\Psi(2S)$ to $J/\Psi(1S)$ suppression is given, and then the theoretical derivation and comparison to experiment is presented.

The mixed Charmonium hybrid theory, with the $\Psi'(2S)$ meson being 50% normal Charmonium and 50% hybrid Charmonium is directly used in calculating the relative suppression.

3.1 Experimental $\Psi(2S)$ to $J/\Psi(1S)$ suppression in p-Pb collisions

The nuclear modification for $\Phi = J/\Psi(1S)$ or $\Psi(2S)$ produced in A-B collisions is defined as[5, 7]

$$R^\Phi = \frac{dN_\Phi^{A-B}/dy}{N_{coll}dN_\Phi^{pp}/dy}, \quad (4)$$

where dN_Φ^{A-B}/dy and dN_Φ^{pp}/dy are the invariant yields of Φ in A-B and pp collisions. In this work we consider p-Pb collisions (A=p, B=Pb).

The relative suppression of $\Psi(2S)$ to $J/\Psi(1S)$ is defined as

$$R^{\Psi(2S)-J/\Psi(1S)} = \frac{R^{\Psi(2S)}}{R^{J/\Psi(1S)}}. \quad (5)$$

The experimental results for rapidity $0 \leq y \leq 3$, as shown in the figure below is

$$R^{\Psi(2S)-J/\Psi(1S)}|_{exp} \simeq 0.65 \pm 0.1 \quad (6)$$

As stated in Refs.[5, 6, 7, 8], the observed suppression of $\Psi(2S)$ compared to $J/\Psi(1S)$ cannot be explained in standard charmonium models. As stated by J. Matthew Durham[6], “the difference in suppression is too strong to be explained by breakup effects in the nucleus...these observations raise interesting questions about the mechanism of $\Psi(2S)$ suppression when it is produced in a nuclear target.”

Recently there was an attempt to explain the $\Psi(2S)$ versus $J/\Psi(1S)$ suppression using a comover interaction approach[20]. In the present work we show that the mixed hybrid theory for the $\Psi(2S)$ state, which has been successful in predicting ratios of $\Psi(2S)$ to $J/\Psi(1S)$ production cross sections in p-p[4] and A-A[21] collisions, can explain the mystery of the $\Psi(2S)$ versus $J/\Psi(1S)$ suppression.

The experimental results for p-Pb (ALICE) and d-AU (PHENIX) collisions are shown in Figure 2, with $\sqrt{s_{NN}} = E_{NN}$ =nucleon-nucleon center of mass energy.

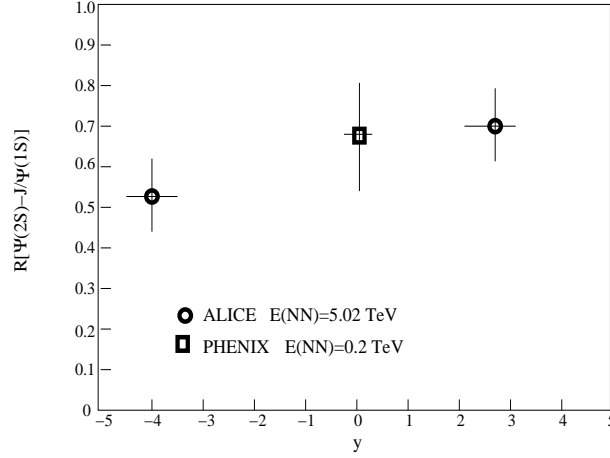


Figure 2: The relative suppression of $\Psi(2S)$ to $J/\Psi(1S)$ for $E_{NN} = 5.02$ TeV p-Pb (ALICE) with rapidity $\simeq -4$ and 3; and $E_{NN} = 200$ GeV d-Au (PHENIX) with rapidity $\simeq 0$

3.2 Theoretical $\Psi(2S)$ to $J/\Psi(1S)$ suppression in p-Pb collisions

The suppression, S_A , of charmonium states is given by the interaction with nucleons as it traverses the nucleus. For a standard charmonium meson state $|c\bar{c}\rangle$ or hybrid meson state $|c\bar{c}g\rangle$, with the $c\bar{c}$ having octet color, the equation for suppression is given by[22]

$$S_A = e^{-n_o \sigma_{\Phi N} L}, \quad (7)$$

where Φ is a $c\bar{c}$ or $c\bar{c}g$ meson, L is the length of the path of Φ in nuclear matter $\simeq 8$ to 10 fm for p-Pb collisions, with nuclear matter density $n_o = .017 fm^{-3}$, and $\sigma_{\Phi N}$ is the cross section for Φ - nucleon collisions.

The cross section for standard charmonium $c\bar{c}$ meson via strong QCD interactions with nucleons is given by[22]

$$\sigma_{c\bar{c}N} = 2.4\alpha_s\pi r_{c\bar{c}}^2, \quad (8)$$

where the strong coupling constant $\alpha_s \simeq 0.118$ [19], and the charmonium meson radius $r_{c\bar{c}} \simeq h/(2M_c c)$, with M_c the charm quark mass. Using $2M_c \simeq M_{J/\Psi} \simeq 3$ GeV,

$$r_{c\bar{c}} \simeq h/(3GeVc) \simeq 6 \times 10^{-17} m = 0.06 fm \quad (9)$$

From Eqs(8,9)

$$\sigma_{c\bar{c}N} \simeq 3.2 \times 10^{-3} fm^2 = 3.2 \times 10^{-2} mb. \quad (10)$$

Taking $L \simeq 8\text{-}10$ fm and $n_o = .017 fm^{-3}$, from Eq(10),

$$\begin{aligned} n_o \sigma_{c\bar{c}N} L &\simeq 0.0022 \\ S_A^{c\bar{c}} &= e^{-n_o \sigma_{c\bar{c}N} L} \simeq 1.0 . \end{aligned} \quad (11)$$

On the other hand, the cross section for hybrid charmonium $c\bar{c}g$ meson via strong QCD interactions with nucleons has been estimated in Ref[22] as $\sigma_{c\bar{c}gN} \simeq 6\text{-}7$ mb. In the present work we use

$$\sigma_{c\bar{c}gN} \simeq 6.5 mb . \quad (12)$$

From this, using $L \simeq 8\text{-}10$ fm and $n_o = .017 fm^{-3}$, from Eq(7) we obtain

$$\begin{aligned} n_o \sigma_{c\bar{c}gN} L &\simeq 0.88 \text{ to } 1.1 \\ S_A^{c\bar{c}g} &\simeq 0.4 \text{ to } 0.33 . \end{aligned} \quad (13)$$

Using our mixed hybrid model, with 50% $|c\bar{c} >$ and 50% $|c\bar{c}g >$, from Eqs(4,11,19), we find

$$\begin{aligned} R^{\Psi(2S)-J/\Psi(1S)}|_{theory} &\simeq \frac{1 + 0.4 \text{ to } 0.33}{2} \\ &= 0.7 \text{ to } 0.66 . \end{aligned} \quad (14)$$

Comparing Eqn(14) to Eqn(6), one finds that the mixed hybrid theory for the state $\Psi(2S)$ solves the mystery of the large suppression of $\Psi(2S)$ vs J/Psi in p-Pb collisions, and therefore in other A-B collisions.

4 Nuclear Modification and Suppression of $\Upsilon(3S)/\Upsilon(1S)$ in Pb-Pb Collisions

This section is similar to the previous one, with the main difference being that we use the experimental results of Ref[16] for the ratios of the standard $\Upsilon(3S)$ to $\Upsilon(1S)$ rather than the theoretical estimate for $\Psi(2S)$ to $\Psi(1S)$ used in the previous section.

4.1 Experimental $\Upsilon(3S)$ to $\Upsilon(1S)$ suppression in Pb-Pb collisions

As stated in Ref[16], although the ratios of observed yields of $[\Upsilon(2S)/\Upsilon(1S)]_{pp}$, $[\Upsilon(2S)/\Upsilon(1S)]_{PbPb}$, $[\Upsilon(3S)/\Upsilon(1S)]_{pp}$, and $[\Upsilon(3S)/\Upsilon(1S)]_{PbPb}$ must be corrected for difference in acceptance and efficiency of the $\Upsilon(2S)$ and $\Upsilon(3S)$ states to the $\Upsilon(1S)$ state, by taking ratio of ratios these corrections are not needed.

The results for the ratio of ratios needed for the present work is

$$\frac{\Upsilon(3S)/\Upsilon(1S)|_{PbPb}}{\Upsilon(3S)/\Upsilon(1S)|_{pp}} = 0.06 \pm 0.06(\text{stat}) \pm 0.06(\text{syst}); . \quad (15)$$

We also use the result from Ref[16] for the $\Upsilon(2S)$:

$$\frac{\Upsilon(2S)/\Upsilon(1S)|_{PbPb}}{\Upsilon(2S)/\Upsilon(1S)|_{pp}} = 0.21 \pm 0.07(\text{stat}) \pm 0.02(\text{syst}); . \quad (16)$$

Since the $\Upsilon(2S)$ state in the theory of Ref[18], upon which the present work is based, is a standard $b\bar{b}$ state, we shall use this modified by the relative bottomium to charmonium nucleation time[22] to estimate the suppression ratio for the standard component of the $\Upsilon(3S)$ state in the next subsection.

4.2 Theoretical $\Upsilon(3S)$ to $\Upsilon(1S)$ suppression in Pb-Pb collisions

In deriving $S_A^{c\bar{c}}$, the suppression for a standard model $c\bar{c}$ state we used Eq(8) to obtain the cross section for standard charmonium-nucleon cross section. Since the $\Upsilon(2S)$ is a standard $b\bar{b}$ state, we can get a more accurate result for standard bottomium suppression Pb-Pb to pp for the $b\bar{b}$ component of the $\Upsilon(3S)$ from Eq(16) modified by the relative neutralization time[22] of $b\bar{b}$ vs $c\bar{c}$ $= \sqrt{M_c/M_b} \simeq 0.55$

$$S_A^{b\bar{b}} = \frac{\Upsilon(3S)/\Upsilon(1S)|_{PbPb}}{\Upsilon(3S)/\Upsilon(1S)|_{pp}}|_{sm} \simeq 0.11 . \quad (17)$$

For the cross section for hybrid bottomonium $b\bar{b}g$ meson via strong QCD interactions with nucleons[22] $\sigma_{b\bar{b}gN} = \sigma_{c\bar{c}gN}(M_c/M_b)^2 \simeq 0.09\sigma_{c\bar{c}gN}$, therefore from Eq(12)

$$\sigma_{b\bar{b}gN} \simeq 0.59mb . \quad (18)$$

Using $L \simeq 15$ fm for Pb-Pb collisions and $n_o = .017 fm^{-3}$, from Eq(7) we obtain

$$\begin{aligned} n_o \sigma_{b\bar{b}gN} L &\simeq 0.15 \\ S_A^{c\bar{c}g} &\simeq 0.017 . \end{aligned} \quad (19)$$

From Eqs(17,19) one obtains

$$\begin{aligned} R^{\Upsilon(3S)-\Upsilon(1S)}|_{theory} &\simeq \frac{.11 + .017}{2} \\ &\simeq 0.06 , \end{aligned} \quad (20)$$

in agreement with the experimental ratio shown in Eq(15), within experimental and theoretical errors.

5 Conclusions

Using our mixed hybrid theory for the $\Psi(2S)$ and $\Upsilon(3S)$ states we have found approximate agreement with experiment for the $\Psi(2S)$ to $\Psi(1S)$ cross section ratio for p-Pb vs p-p collisions, and the $\Upsilon(3S)$ to $\Upsilon(1S)$ cross section ratio for Pb-Pb vs p-p collisions.

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